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Development of a split mold for internal consolidated undrained isotropic compression (CUIC) testing of low effective-stress soils from slurry

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**Development of a split mold for internal consolidated undrained isotropic compression
(CUIC) testing of low effective-stress soils from slurry**

by

Adam Maher

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering

Program of Study Committee:
Cassandra Rutherford, Major Professor
Vernon Schaefer
Peter Savolainen

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

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DEDICATION

This thesis is dedicated to my daughter Flannery Kate Maher and to my grandfather Earl A. Sibley (1926-2013) who was a prominent Geotechnical Engineer in Seattle, Washington.

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ABSTRACT

Soft, flowable soils are problematic materials that are frequently encountered in geotechnical projects. These materials include soft marine clays, mine tailings, and dredged sludges. Soft marine clays which have a high liquid limit, have an in situ water content close to or above its liquid limit, and are sensitive are often encountered in marine settings in the design of offshore foundations, in hazard mitigation for submarine landslides, and in the installation of pipelines in the top few meters of seabed. Clays near the surface have the lowest strength due to no overlying self-weight and resultant low effective stress. These clays are often non-self-supporting - highly flowable - and thus are very difficult to test in a laboratory setting.

A previously developed internal split mold technique that allows a non-self-supporting material to be tested in triaxial shear compression with the application of a small confining pressure, and then consolidated and sheared as normal. Tests performed using this method have only been limited to mine tailings, sand, and dredged sludge, and has not been used to consolidate and test soft clays.

The objectives of this research study were to further develop the internal split mold technique and examine how it can be applied to soft clays at very low effective stresses (20 - 30 kPa) corresponding to the upper several meters of seabed. Three Consolidated Undrained Isotropic Compression (CUIC) triaxial shear tests were conducted on pulverized Kaolin (PL = 41%, LL = 62%) mixed to a slurry at 100% water content. The stress-strain data were then analyzed and compared to published strength behavior of Kaolin clay.

CHAPTER 1. BACKGROUND

The mechanical behavior of soft materials have been typically tested using field devices such as the T-Bar penetration tests and field vane shear tests. Stewart and Randolph (1991) developed a full flow penetrometer approach that involved the combination of a Cone Penetration Test (CPT) and a field Vane Shear Test (VST) called a T-Bar Penetrometer (Figure 1.1). This in-situ test provides the benefits of the CPT to obtain a continuous profile of shear strength while using an attached T-Bar instead of a cone to overcome the inaccuracies of CPT strength measurements by empirical correlations in very soft soils (Randolph and Gourvenec, 2011).

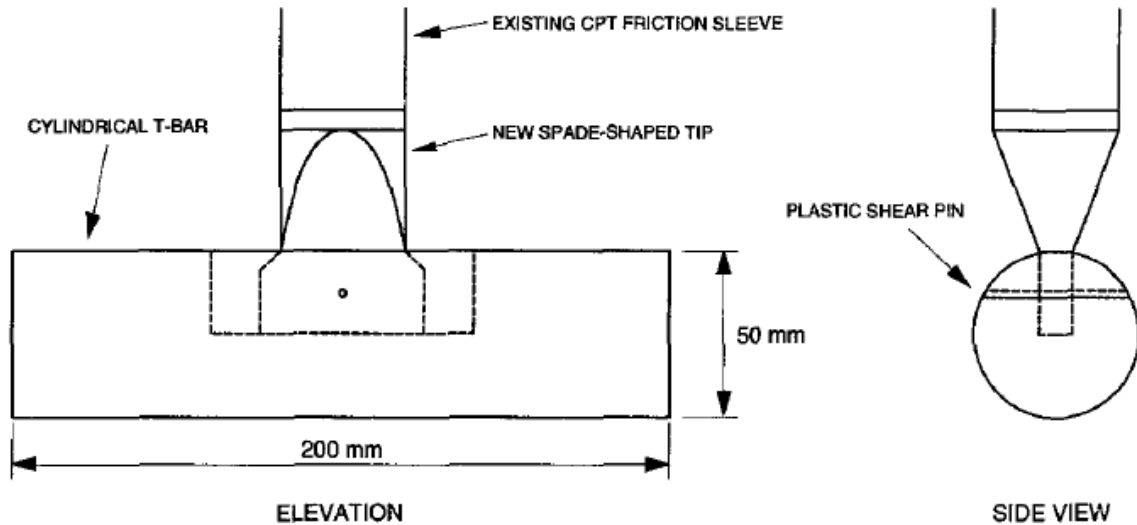


Figure 1.1 *T-Bar Penetrometer attached at the end of a CPT rod (Stewart and Randolph, 1991).*

The T-bar Penetrometer is the standard used in offshore site investigation currently most robust testing procedure for analyzing the strength behavior of the upper 1-2 meters of

the seabed for pipeline and riser design (Randolph and Gourvenec, 2011). Tests are usually run in-situ or inside of a box core sample (Boscardin, 2013). Tufebkjian and Thompson (2010) used a tank where Kaolin slurry was reconsolidated corresponding to the top few meters of ocean bed and obtaining an undrained shear strength profile using a T-Bar penetrometer. An important parameter for design is the soil grain to grain and soil-structure frictional resistance that can only best be determined when stress-strain behavior has been simulated in a controlled manner.



Figure 1.2 *Laboratory reconstituting technique of Kaolin slurry (Tufebkjian and Thompson, 2010).*

As with the normal CPT and with field tests in general, the T-Bar Penetrometer cannot consolidate the soil being tested hence being unable to accurately simulate the stress-strain behavior of these soils. In order to most accurately describe low-effective stress soft soils for design and constitutive models, laboratory tests need to be performed. There exists two major laboratory tests that have been used in the literature to test these soils: tilt tables (Pederson et al., 2003) and surcharge consolidation (Krizek and Sheeran, 1970). The fundamental issue with testing soft soils is the sample preparation methods for these tests. Soft soils are often non-self-supporting and cannot be easily prepared for testing without first inducing a small-strain consolidation to make it self-supporting. The slurry reconstitution technique shown above in Figure 1.2 from Tufekjian and Thompson (2010) is similar to what was initially developed in Krizek and Sheeran (1970) is a common way to make a soil sample which “erases” the stress history of the soil by allowing reconsolidation of the soil to any given pressure. This process includes mixing soil at a water content in the range of one to six times the liquid limit of the soil and placing in a vacuum for an extended period of time.

Currently, soft materials are initially consolidated using a dead weight consolidometer and then sheared in a triaxial test. Most generally, this process involves reconstituting the soil and placing inside of a pipe with porous stones on either side of the specimen (Krizek and Sheeran, 1970). A vertical surcharge is then applied to the top stone and the soil is allowed to consolidate as water is drained through the bottom porous stone. Once the soil is consolidated to a state in which it is self-supporting, it is extruded from the pipe, trimmed, and prepared for shearing in the triaxial test. This process has inherent sample disturbance limitations that include unloading, trimming, and small-strain consolidation.

McManus and Kulhawy (1991) mixed Kaolin clay with water at two times the liquid limit ($w = 116\%$) and consolidated the specimen with load increments of vertical surcharge in a large-scale laboratory prepared slurry deposit. Time was measured and a coefficient of consolidation could be calculated thus providing the framework for knowing the load and time needed to make a firm clay sample with a given water content. Consolidated isotropic undrained triaxial compression tests were run on samples cored from the laboratory deposit. The method inherently involves partial consolidation, unloading, and reconsolidation providing for several opportunities for sample disturbance.

Saebimoghaddam (2010) developed a unique deadweight surcharge technique by preparing a specimen in a split mold with a membrane, porous stones, and platens (Figure 1.3). The specimen could then be consolidated using the triaxial device and the split mold could be removed resulting in less disturbance from the extrusion and trimming process. This process still has inherent in it the unloading of the specimen to zero confining pressure and still showed an unrealistic decrease in overall porosity of mine tailing samples that results in inaccurate stress-strain states. Saebimoghaddam (2010) was able to quantify this inaccuracy by measuring the void ratios at the top, middle, and bottom of each specimen after consolidated in the surcharge and found variations in these values.

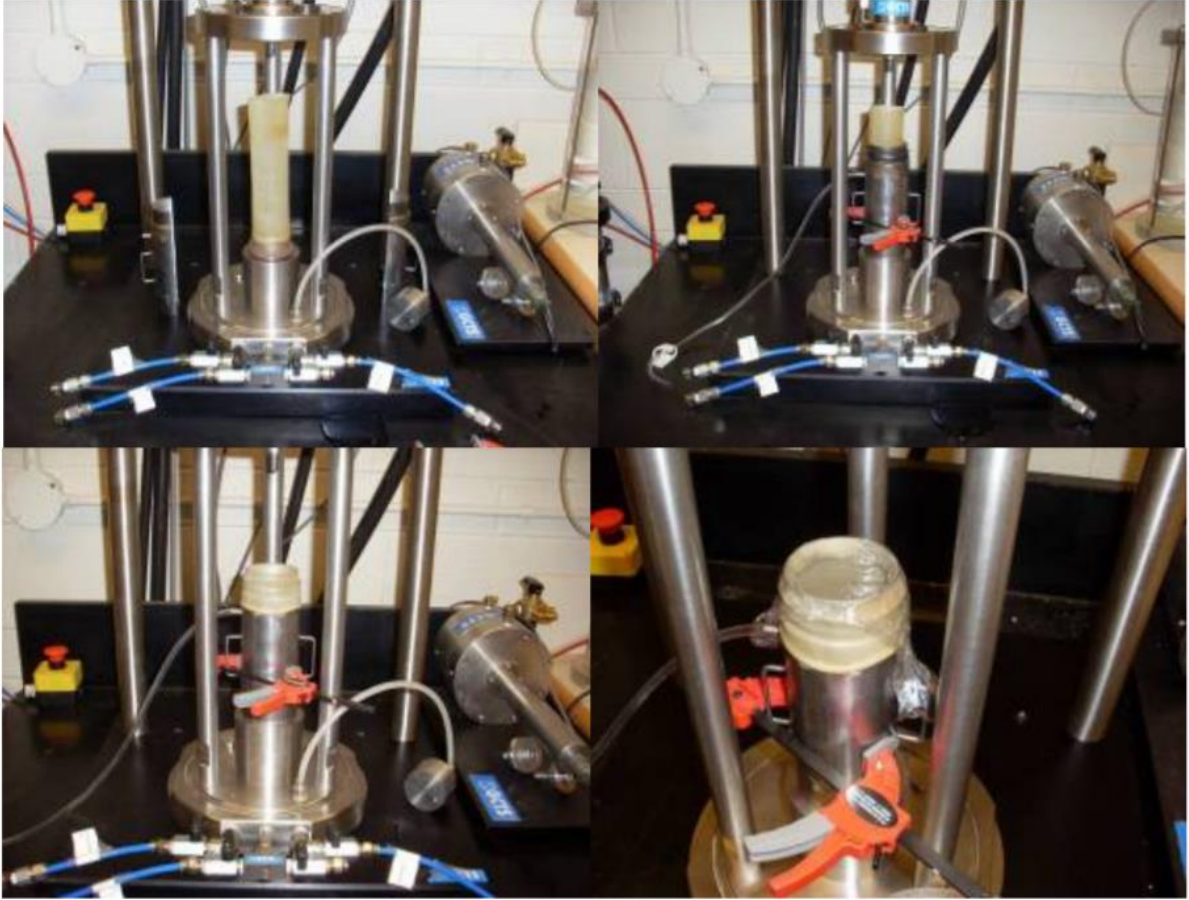


Figure 1.3 *Sample preparation method for consolidating specimen in split mold and consolidating with triaxial piston (Saebimoghaddam, 2010).*

The inability to simulate consolidation and shearing behavior in one method is a limitation to obtaining reliable data for design and constitutive models. Pederson et al. (2003) tried to overcome the sample preparation problem by using a tilt table (Figure 1.4). They developed the concept which has been used in in rock mechanics and geosynthetics to test Kaolinite from slurry at low effective pressures (1 - 2400 Pa) to examine the internal shear strength of soft Gulf of Mexico clays and external shear strength along Suction Caissons used for floating offshore foundations. A thin specimen direct shear test (TSDS) is prepared on the apparatus by pouring the slurry in a film and allowing to consolidate under a dead weight.

The specimen is then submerged in a tank on a table which is then inclined by 1-degree increments until visible failure occurs in the specimen or along the platen surface. Stresses at failure are calculated using average shear and normal stress equations by dividing the dead weight by the area and multiplying by the sine and cosine of the inclination angle respectively.

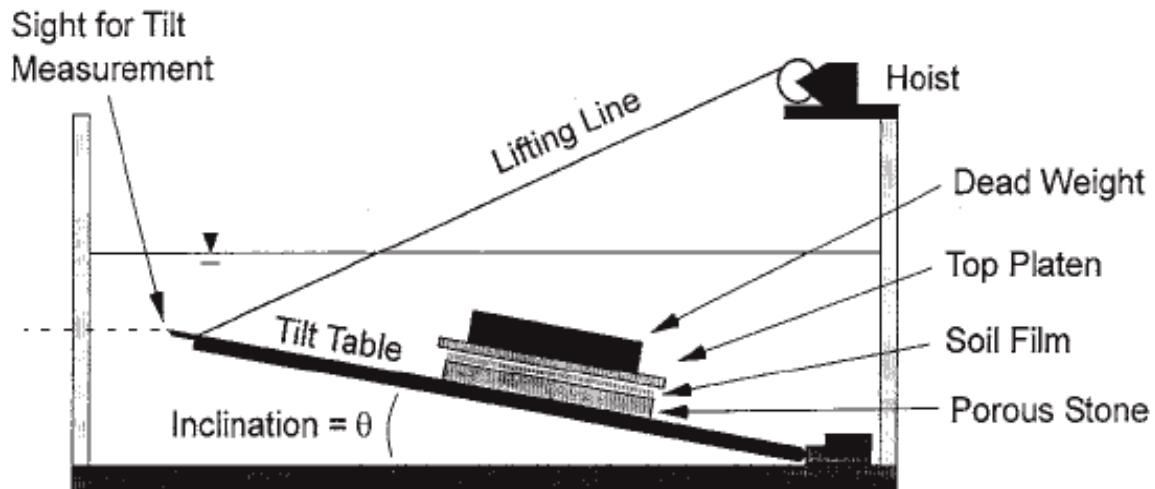


FIG. 2—Tilt-table apparatus used in thin-specimen direct shear (TSDS) tests.

Figure 1.4 Schematic diagram of the tilt table (Pederson et al., 2003).

The tilt table provides obvious disadvantages to measuring strengths including the inability to measure displacements in the material and limited surcharge weights due to possible toppling. However, it does provide a unique test for measuring soft soils at low effective stresses and does not force a failure plane.

Zhu et al. (2014) introduced an innovative sample preparation technique for non-self-supporting materials that have high moisture contents and high flowability. Their research primarily focused on mine tailings and dredged sludge and not reconstituted clays. The technique overcomes many limitations to testing soft materials by uniting consolidation and shearing into one process. Zhu et al. (2014) introduced a split-mold (Figure 1.5) in which the sample can be prepared inside of and placed in the triaxial cell applying a small confining pressure to make the soil self-supporting. The mold can then be opened using a hook on the piston, and the sample is then consolidated and sheared. By making the sample self-supporting inside of the triaxial cell, the split-mold method allows for consolidation and shearing to be united.

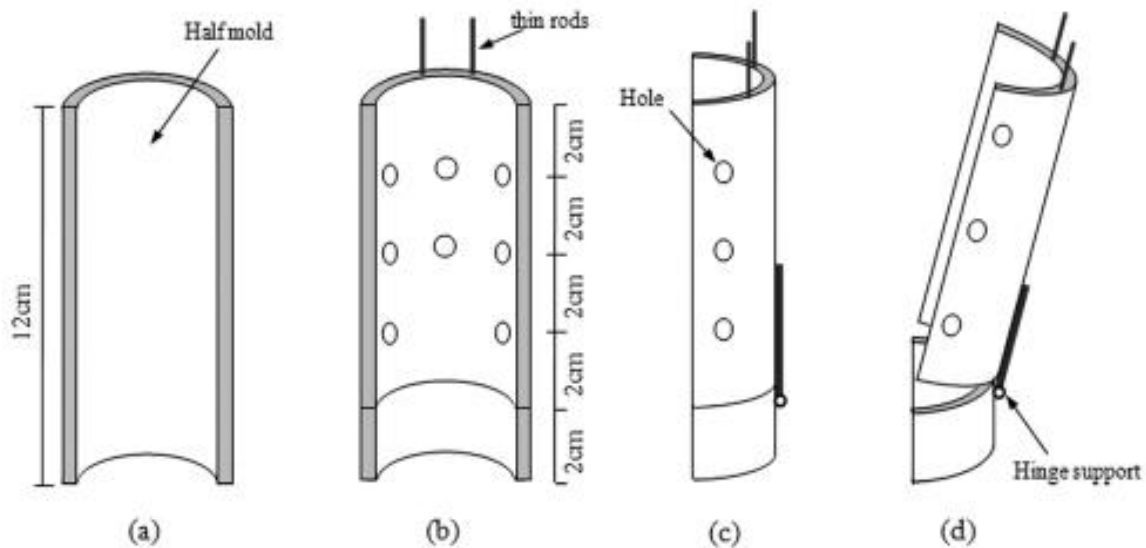


Figure 1.5 Split mold design (Zhu et al., 2014).

Figure 1.6 below from Zhu et al. (2014) shows the step-by-step loading procedure of a sample in the split mold in the triaxial test. The sample is prepared in the split mold on the triaxial base, and a set of rubber bands are attached to screws on the top of the mold (Rubber

band Group A) to keep the mold closed. Another set of rubber bands (Rubber band Group B) are attached from the top of the mold to the base of the triaxial cell to provide an opening mechanism. The triaxial chamber is then pressurized and a small confining pressure is applied through the holes in the split mold. This small confining pressure (5 kPa) makes the soil sample self-supporting thus allowing the mold to be removed. The mold is opened by lowering the piston and allowing the hook to grab on to and remove Rubber band Group A causing the mold to open. After the mold has been open, saturation, consolidation, and shearing can proceed as in a conventional triaxial shear test.

Zhu et al. (2014) notes two major challenges in obtaining accurate data from the improved method. These challenges include whether or not the small confining pressure is uniformly applied through the small holes in the mold, and whether or not the opened mold interferes with the deformation of the specimen during shearing. The mold needs to be thin enough that when it opens and rests on the side of the chamber there is enough space for the specimen to deform laterally.

Comparing to the traditional method of vertically loading the specimen to a desired consolidation pressure and performing the improved method by first removing the mold prior to consolidation, Zhu et al. (2014) found that the improved method resulted in a more uniform specimen that could stand vertical on its own with no tilt unlike the traditionally prepared specimen.

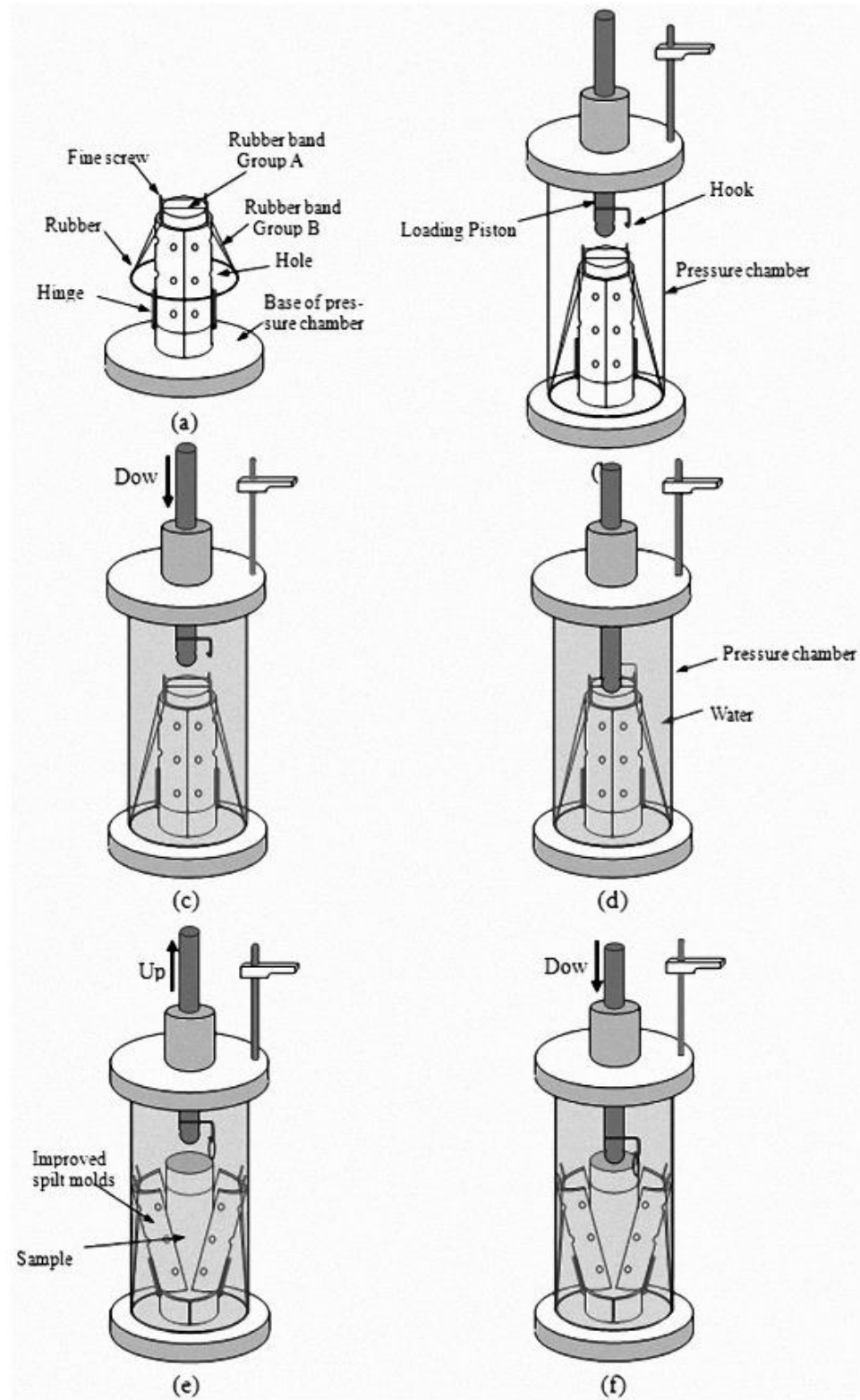


Figure 1.6 Loading procedure of the triaxial test using the split mold from Zhu et al. (2014).

The stress-strain data obtained in Zhu et al. (2014) reveal that is consistent with data in the literature while also showing consistent void ratio values throughout the specimen's height. Thus the improved split mold method was shown to be a viable option for obtaining the stress-strain behavior of materials that are difficult to prepare in a triaxial test due to their high water contents.

Gaps in the research of Zhu et al. (2014) is that only cementitious materials, dredged sludge, and sand were tested at 100 kPa consolidation and no types of cohesive soils found in nature were tested. Additionally, the water contents of the materials (besides sand) were only in the 60% range. Hence, the method remains to be used on different soil types at different consolidation pressures.

CHAPTER 2. DEVELOPMENT OF THE SPLIT MOLD

The mold developed by Zhu et al. (2014) was fabricated using the approximate dimensions provided in Figure 1.5. Using a 1.4 inch diameter specimen, enough space had to be available for the base of the mold to fit around the O-rings. 1.66 inch diameter provided enough space and the same diameter was used for the sides of the split mold to ensure enough distance from the membrane along the sides of the specimen. Figures 2.1 and 2.2 show AutoDesk drawings of the base and sides of the split mold.

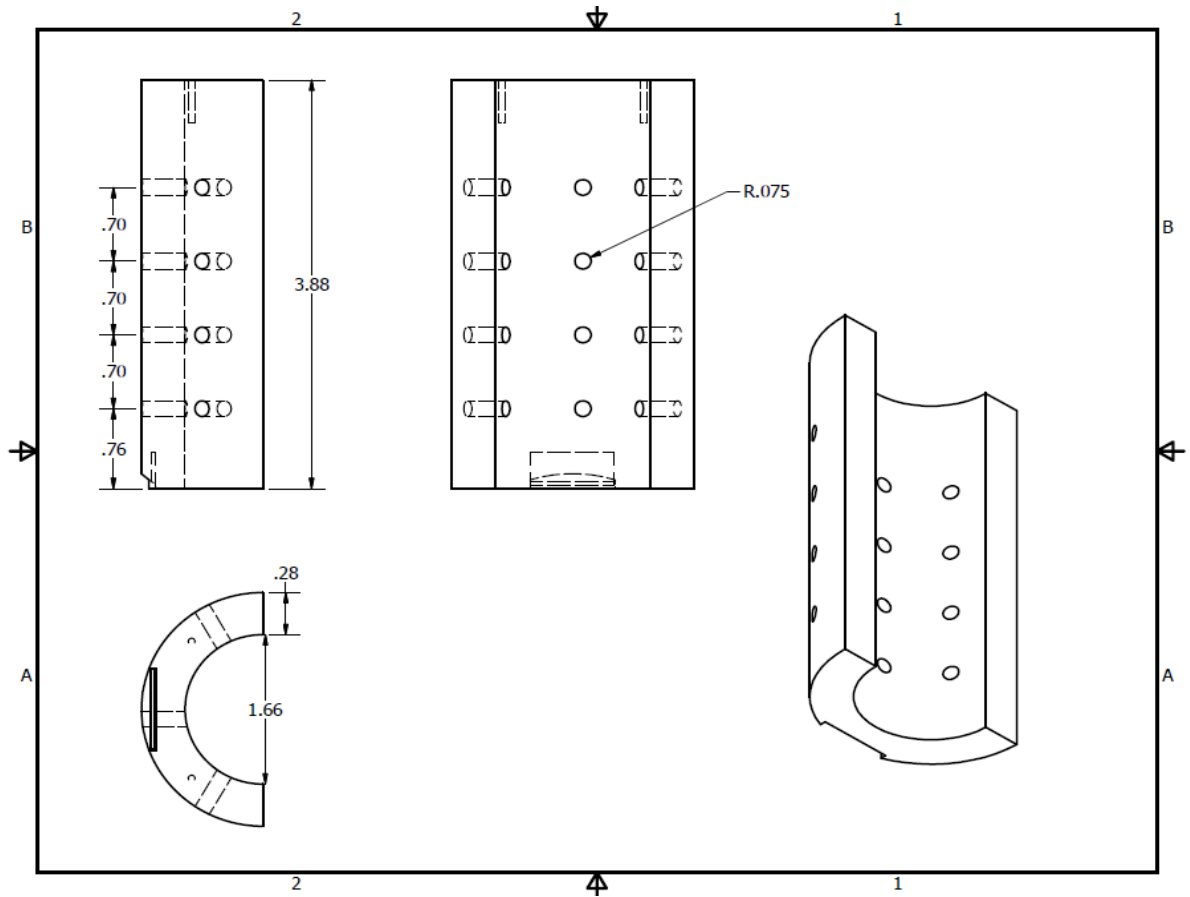


Figure 2.1 AutoDesk drawing of the sides of the split mold.

A fourth and fifth hole had to be added to the top of the mold, so that rubber band group A would not interfere with the top cap. Another difference included adding an extruding edge to the base for rubber band group B to attach to instead of being attached at the base of the o-ring of the triaxial cell. Metal corner hinges were used to connect the base of the mold to the sides. Super glue was applied in the divots where the hinges were placed to ensure the connection.

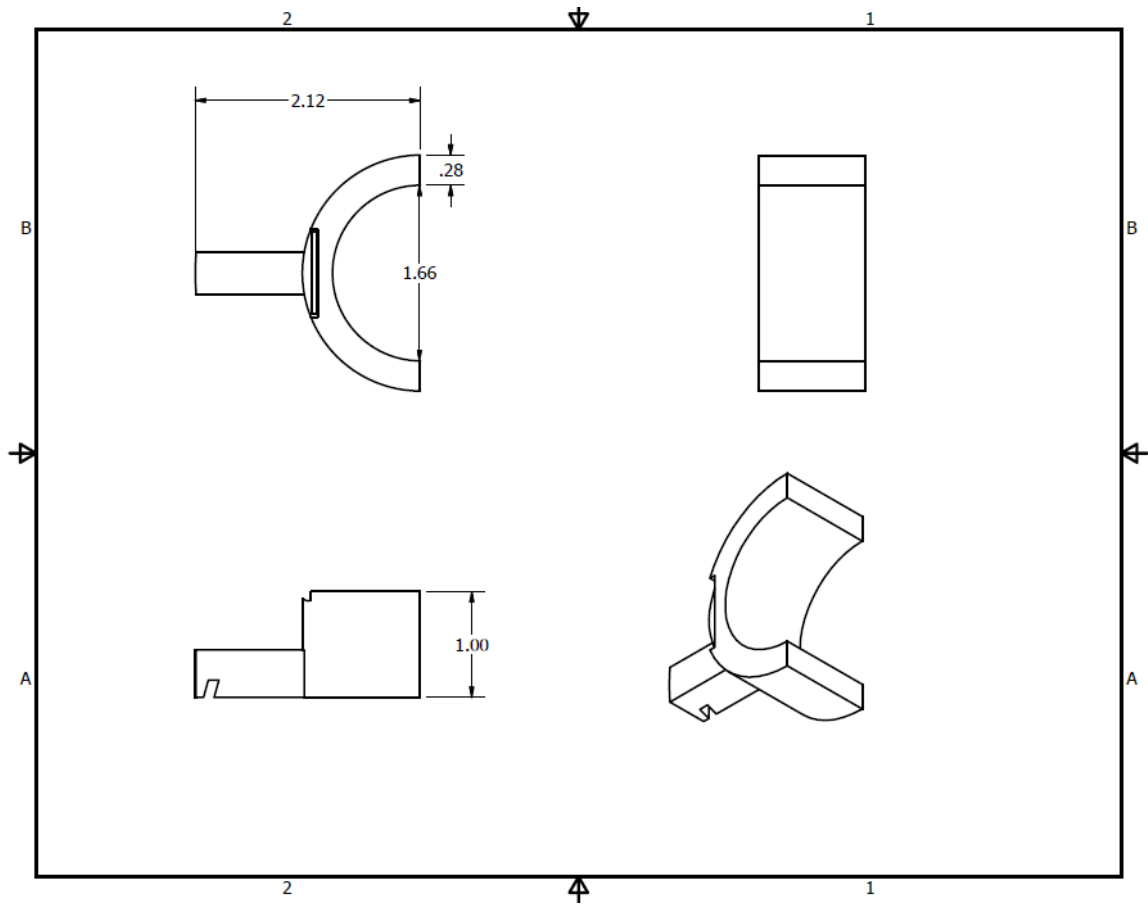


Figure 2.2 AutoDesk drawing of the base of the split mold.

The mold was 3-D printed at the Iowa State Center for Education, Learning and Teaching (CELТ). The material used in the printer was a plastic filament that needed to provide a dense enough composition that the divots for the hinges and screws could be secured. Three shells with a 20% filament density was used to ensure this condition. The parts took approximately 10 hours in total to print and proved to be a cost-effective and time-saving method for developing the split mold.

After printing, the sides and base of the mold were connected with a hinge attached in the divots seen in Figures 2.1 and 2.2 by placing super glue on each side of the hinge and being allowed to set for twenty four hours. Six 1/16 inch holes were drilled into the top of the sides of the mold to allow for the placement of the nails where the rubber band groups could attach to. The printed mold is shown below in Figure 2.3.

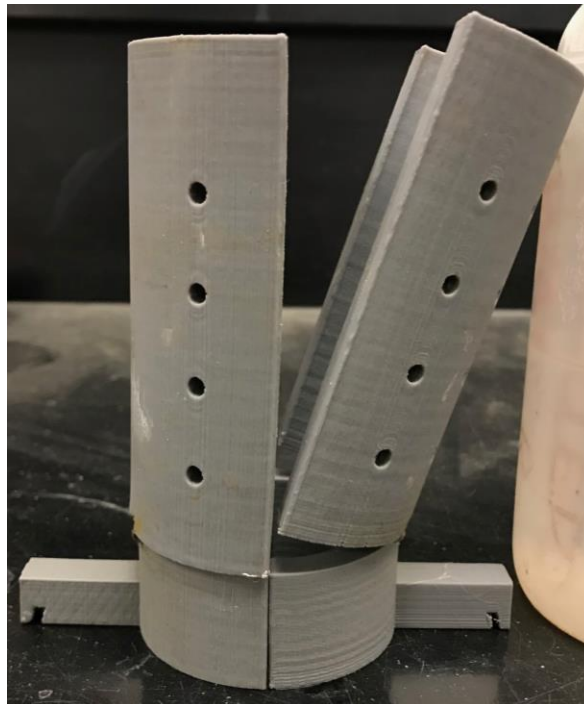


Figure 2.3 3-D printed split mold.

The main modifications made in this research to the mold from Zhu et al. (2014) include the addition of a small notch in the base of the mold, two additional holes in the top, and an internal hinge location. The small notches on the base of the mold were used to connect the rubber band group that opens the mold instead of attaching the rubber band around the o-ring of at the base of the chamber. Two additional holes at the top of the mold were used for additional nails that hold the upper rubber band in place. The 3-D mold was designed to have space for an internal hinge support instead of the external hinge used in Zhu et al. (2014).

CHAPTER 3. EXPERIMENTAL PLAN

The purpose of this research is to analyze the soil types found in the upper 1 to 2 meters of the seabed using the improved method by mixing a clay from a slurry. Pulverized kaolinite was utilized as a clay material that was mixed at a water content approximately 1.5 to 1.75 times its liquid limit and consolidated at a pressure of 30 kPa.

The triaxial test equipment used in this research are listed below:

- Triaxial cell with rounded piston tip
- Aluminum wire for hooking top rubber band
- 1.4 inch diameter porous stones, filter papers, O-rings, and top and bottom caps
- 1.4 inch diameter and 0.012 inch thick latex membranes
- 3-D printed split mold device
- 2 rectangular cut filter papers for the inside of the mold
- Flexible tubing for back-pressure and pore-pressure measurements
- 6 1/16 inch diameter and 2 inch long nails with heads removed
- 3 rubber bands
- 2 screws for connection to triaxial base
- 2 zip ties to secure the mold to the base
- Vacuum grease

The experimental plan followed in this research is generally described by the following eleven-step procedure:

1. *Mixing slurry*
2. *Split mold preparation*
3. *Pouring slurry into split mold*
4. *Placing stone, top cap, and O-rings*
5. *Attaching rubber band groups and tubing*
6. *Securing triaxial cell, filling with water, and hooking rubber band*
7. *Applying 5-10 kPa confining pressure*
8. *Opening split mold with hook*
9. *Saturation*
10. *Consolidation*
11. *Shearing*

1. *Mixing slurry*

The slurry was prepared by mixing 2 kg of pulverized Kaolin powder with 2 kg of distilled water with an auger attached to a drill making a water content of 100%. The mixture was subjected to a 5 psi vacuum pressure in a sealed bucket for 48 hours. The mixture was stirred each time prior to taking a sample out for testing as water accumulates on the surface of the mixture after sitting at rest for an extended period of time. Figure 3.1 shows the materials used to create this mixture.



Figure 3.1 *Slurry preparation materials.*

2. *Split mold preparation*

Several steps were taken to ensure the split mold was attached inside of the cell securely and that the slurry could be poured into with ease. The 1.4 in. porous stone, filter paper, and membrane (0.012in. thick) were placed on the bottom cap with vacuum grease. Two O-rings were placed over the membrane (Figure 3.2a). Two pieces of filter paper were placed over the sides of the split mold to ensure pressure was equally applied to the sample. The split mold was then secured over the bottom cap (Figure 3.2b) and zip ties were used to secure the bottom of the split mold to

screws attached to the base of the triaxial cell. The sides of the mold were then secured using several rubber bands that were detached prior to filling with cell pressure (Figure 3.3). The membrane was then rolled over the sides of the mold for the placing of the slurry (Figure 3.3).

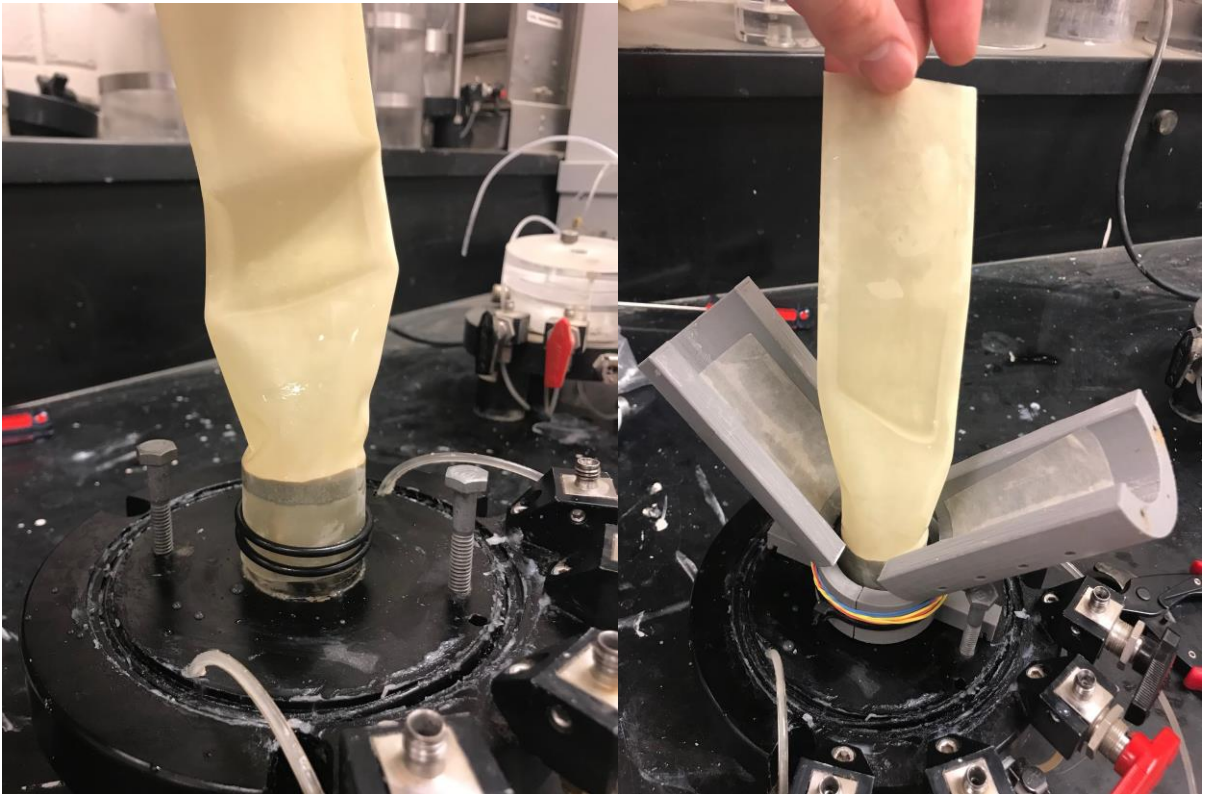
*a.)**b.)*

Figure 3.2 *a.) attachment of the porous stone, filter paper, membrane, and O-rings to the bottom cap. b.) placing of the split mold over the bottom cap with filter paper lining the inside.*

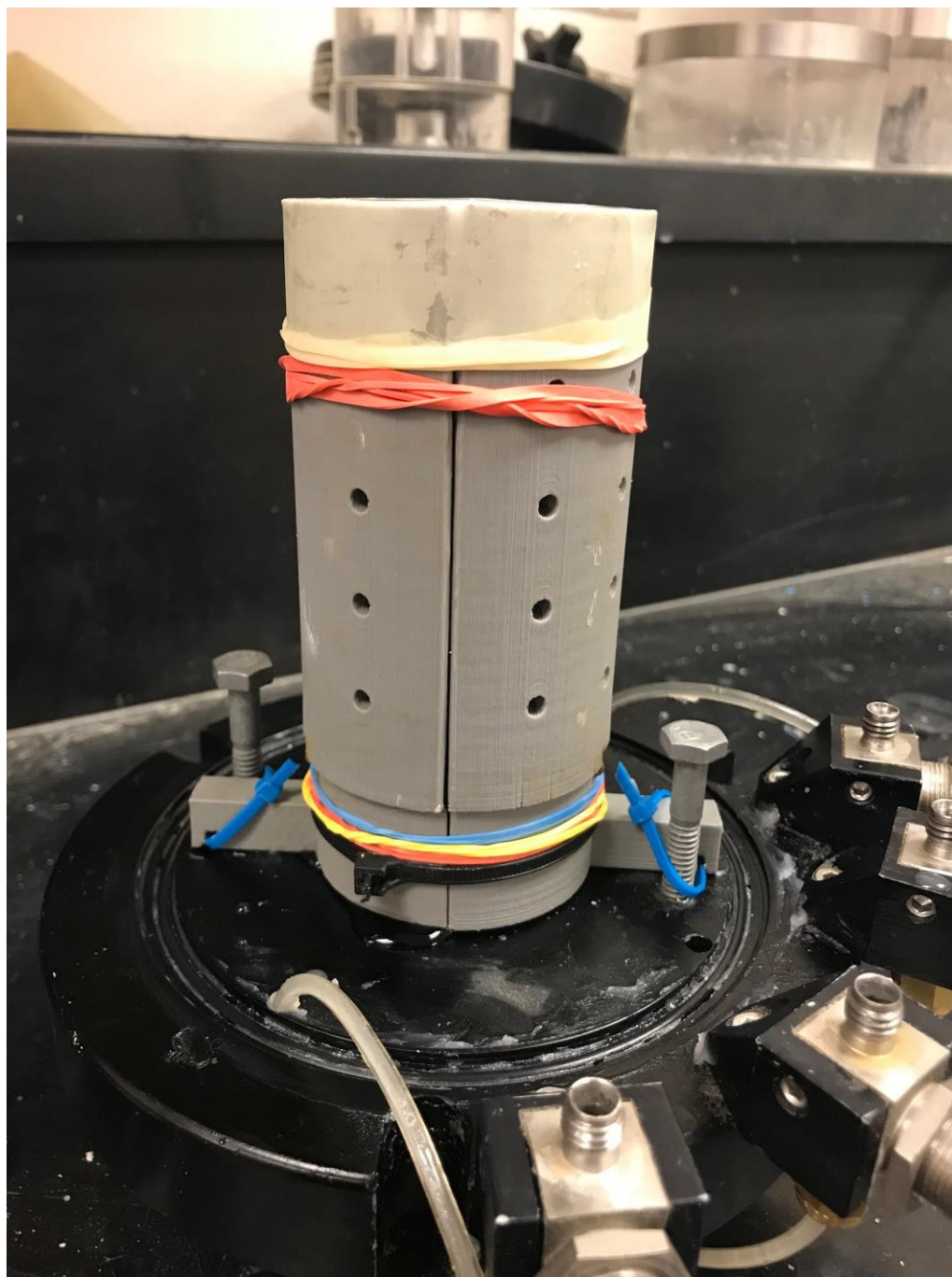


Figure 3.3 *Securing of the split mold to the base of the triaxial cell with zip ties. Temporary rubber bands placed around mold to maintain closure during sample preparation. Rolling of the membrane over the top of the split mold.*

3. *Pouring slurry into split mold*

The amount of slurry was measured and poured into the mold in several layers gently mixing the slurry with a small spatula after each layer. Pouring was stopped once the height of the slurry reached about 0.5 inches below the top of the split mold (Figure 3.4). In each test, this corresponded to about 100 grams of slurry.



Figure 3.4 *Pouring of the slurry into the mold stirring with a spatula to a height of about 0.5 inches below the top of the mold.*

4. *Placing filter paper, stone, and top cap*

The filter paper, stone, and top cap were placed very carefully on top of the slurry. The membrane was rolled off the sides of the mold and secured on the top cap with two o-rings (Figure 3.5).

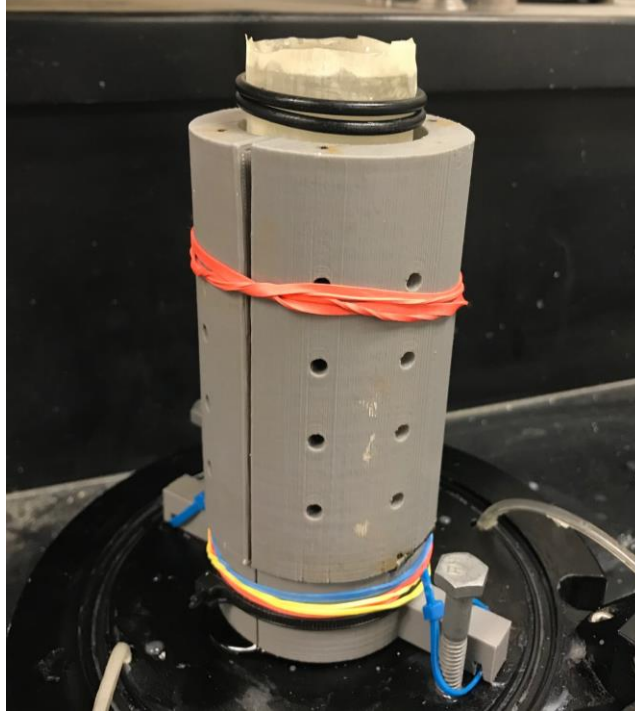


Figure 3.5 *Placing of the filter paper, top cap, and O-rings at the top of the sample.*

5. *Attaching rubber band groups and tubing*

Six nails were placed in the drilled holes in the top of the mold and the first set of rubber bands were attached from the base of the split mold to the top (Figure 3.6a). Then mold had to be slightly raised to attach the rubber bands underneath the base and into the divots. The nails had to be placed deep enough into the mold that they did not bend when the rubber bands were wrapped around them. The second group of rubber bands were placed around four of the nails to keep the mold closed (Figure 3.6b). Both groups of rubber bands were double wrapped to ensure enough tension was in place to hold the split mold together and remove maintain its opening. After both groups of rubber bands were attached, the rubber bands wrapped around the sides of the mold were removed by cutting with a scissors.

The tubing for the drainage lines were then attached to the top cap by placing underneath the top rubber band in order to not be interfered with when the rubber band was removed. The tubing needed to be flexible enough that when the mold was initially removed it did not cause a torque on the soft clay specimen enough to prevent it from standing vertically while not being flexible enough that small cell pressures could pinch the tubes closed. Since the sample is very soft, much care was taken to place the tubes into the top cap without compressing the specimen.

a.)



b.)



Figure 3.6 a.) Attachment of first rubber band group from the top of the mold to the base. b.) Attachment of the second rubber band group at the top of the mold and placement of the tubes into the top cap.

6. *Securing triaxial cell, filling with water, and hooking rubber band*

The triaxial cell base was cleaned thoroughly after sample preparation to ensure no material was in the space where it connects to the sides of the cell. The cell was then secured together using vacuum grease on all openings, and the piston was manually lowered to ensure it could come into contact with and wrap around the top rubber band without interfering with the specimen (Figure 3.7a). The cell was then filled with tap water (Figure 3.7b) and cell fluid pressure applied and allowed to sit for several minutes to saturate the mold enough where air bubbles no longer came out.



Figure 3.7 a.) Wire wrapping around the top rubber band. b.) Filling of the triaxial cell with water through a permeability panel.



Figure 3.8 *Aluminum wire hooking around the top rubber band.*

7. Applying 5-10 kPa confining pressure

After the pore-water-pressure transducer, back pressure pump, and cell pressure pump have been connected to the triaxial cell, a small 5-10 kPa confining pressure was applied to make the specimen self-supporting.

8. *Opening split mold with hook*

The piston was then lifted up and the hook removed the top rubber band causing the other rubber bands to open the split mold in tension (Figure 3.9). In order to avoid unwanted pressure reduction, the piston had to be lowered slowly enough that the cell pressure did not decrease to below 5 kPa. The piston was then lowered to come into contact with the top cap slow enough to avoid any unwanted pressure increases. The specimen was usually slightly tilted, but could be corrected using a rounded piston to bring the center of the top cap back into vertical alignment with the piston (Figure 3.9).



Figure 3.9 Opening of the split mold and lowering of piston to come into contact with the top cap.

9. Saturation

Using the volumetric pressure pumps, saturation was performed automatically while checking the B-value throughout. A B-value of 0.95 was usually achieved below 100 kPa due to the slurry being almost completely saturated to begin with. Saturation is detailed more in the Equipment and Software section.

10. Consolidation

Consolidation was done at a rate of increase in cell pressure of 5 kPa/hour. All tests were carried out between 20-30 kPa corresponding to the top 1-2 meters of sediment given a unit weight of 15 kN/m³. Consolidation pressure more than 30 kPa needs to be avoided if using a high water content slurry since consolidation will result in significant pore-water dissipation and consequent volume change. This volume change begins to affect the diameter of the specimen due to the folding of the membrane. Consolidation is detailed more in the Equipment and Software section.

11. Shearing

Shearing was done at a rate of 0.5% axial strain per hour and terminated around 30% strain. Shearing is detailed more in the Equipment and Software section.

CHAPTER 4. EQUIPMENT AND SOFTWARE

The Geotac TruePath automated load test system was utilized in this research to carry out the CUIC Triaxial tests according to ASTM D4767-11. This section describes each major component of the system and how data was obtained in an effective and meaningful way.

Figure 4.1 shows the setup used in the testing of the Kaolinite clay. This setup consisted of a load frame, a cell pressure volumetric pump, a back pressure volumetric pump, and several pieces of hardware used to record and obtain data in the DigiFlow-GP System software.

A schematic view of the load frame is seen in Figure 4.2. The bottom platen is connected to a screw-jack which measures the axial deformation of the sample. The piston is in contact with an external axial load cell with a 2000 lbs (8.895 kN) load capacity. A level was used to ensure that the crosshead was parallel to the bottom platen so the piston was at a 90 degree angle to the crosshead when coming into contact with the axial load cell. The setup and connection of the load frame to the computer is shown in Figure 4.3. Two serial cables are used to connect from the load frame to the network module and then to the computer. The axial load cell and pore-water-pressure transducers are connected to the load frame

The two volumetric pressure pumps were used to automate the saturation and consolidation process of the triaxial shear test. Each pump had a 2000 kPa pressure capacity with a 75 mL volume capacity of the back-pressure pump and a 170 mL volume capacity of the cell pressure pump. Each pressure pump was filled and drained using the refill line to a de-aired water container (Figure 4.4). Since the soil tested had such a high initial water content, the back pressure pump needed to be almost completely emptied prior to testing.

Pressure transducers are attached to each of the pumps seen in Figure 4.5. The pumps are connected to the computer via the network module with a serial cable coming from one of the pumps.

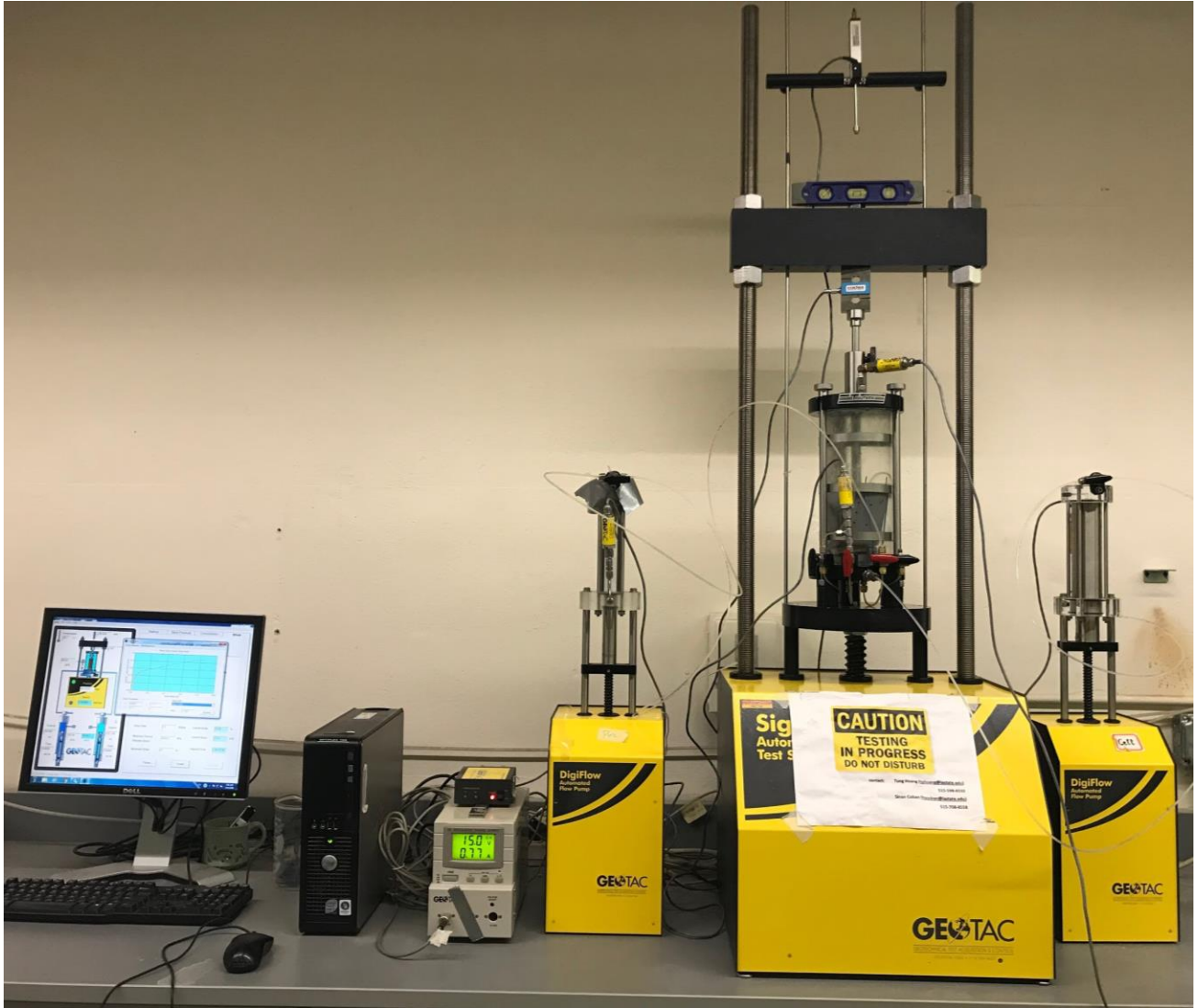


Figure 4.1 Geotac TruePath automated load test system used for testing.

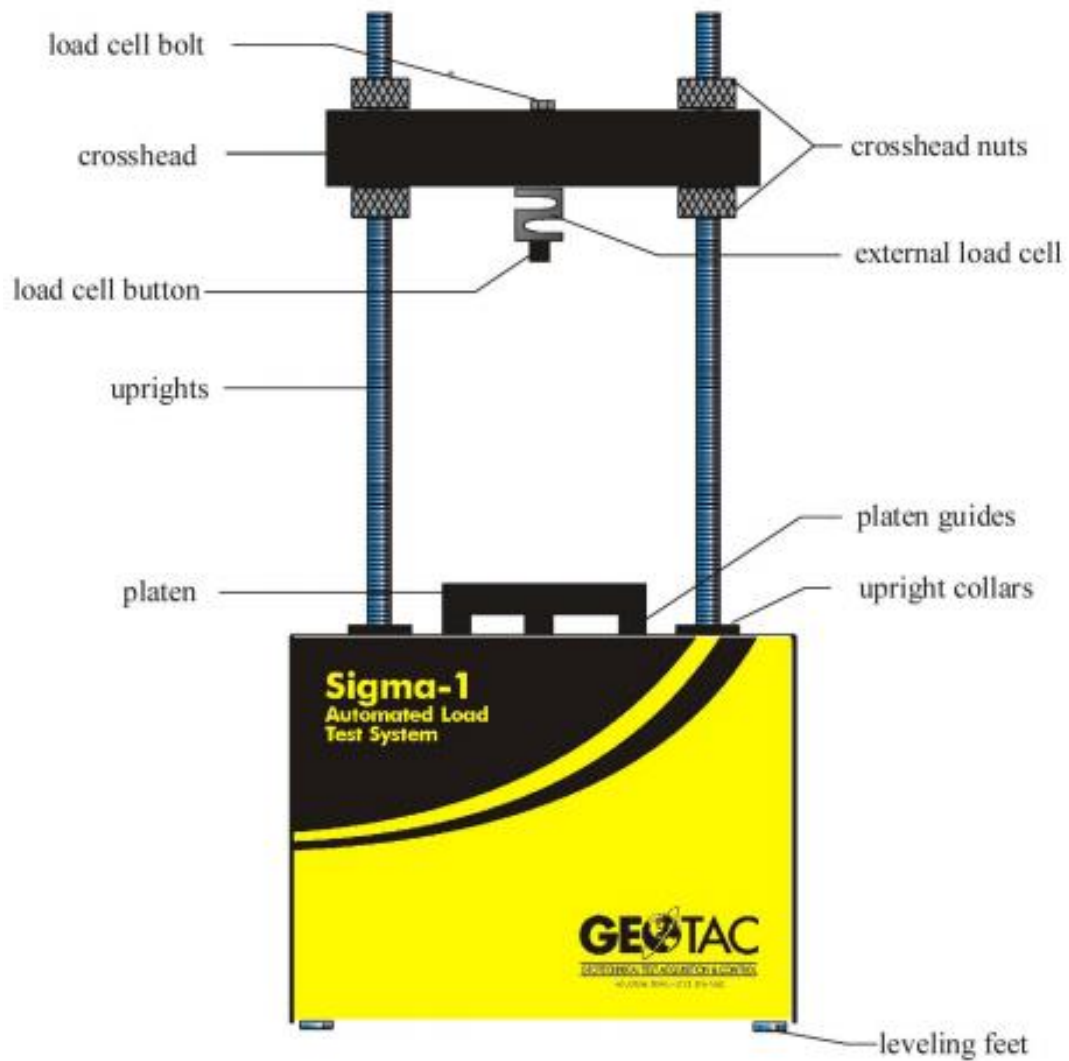


Figure 4.2 Geotac load frame schematic view with each part defined (Trautwein Soil Testing Equipment Company, 2003).

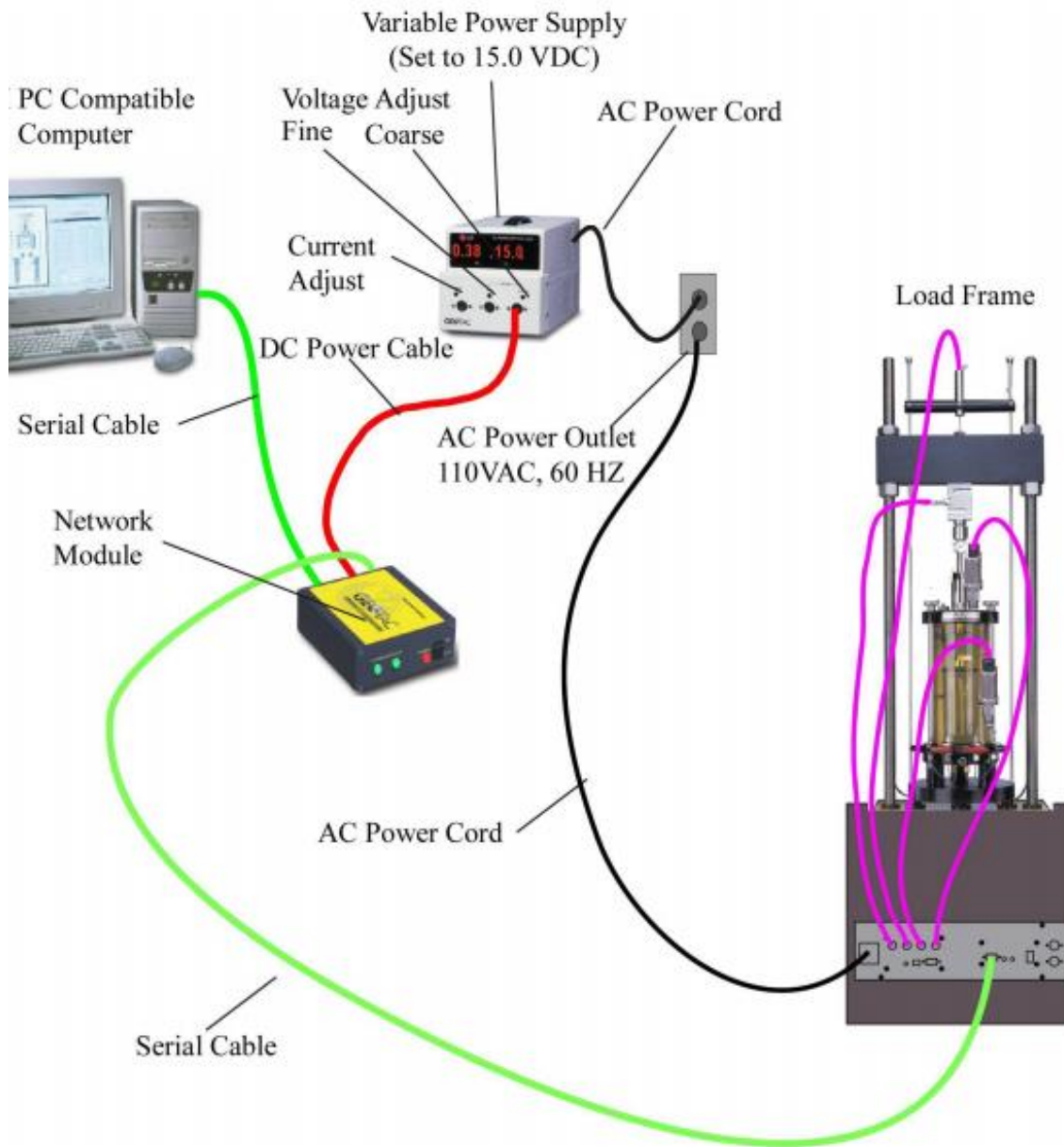


Figure 4.3 Schematic view of the GeoJac load frame setup (Trautwein Soil Testing Equipment Company, 2000).

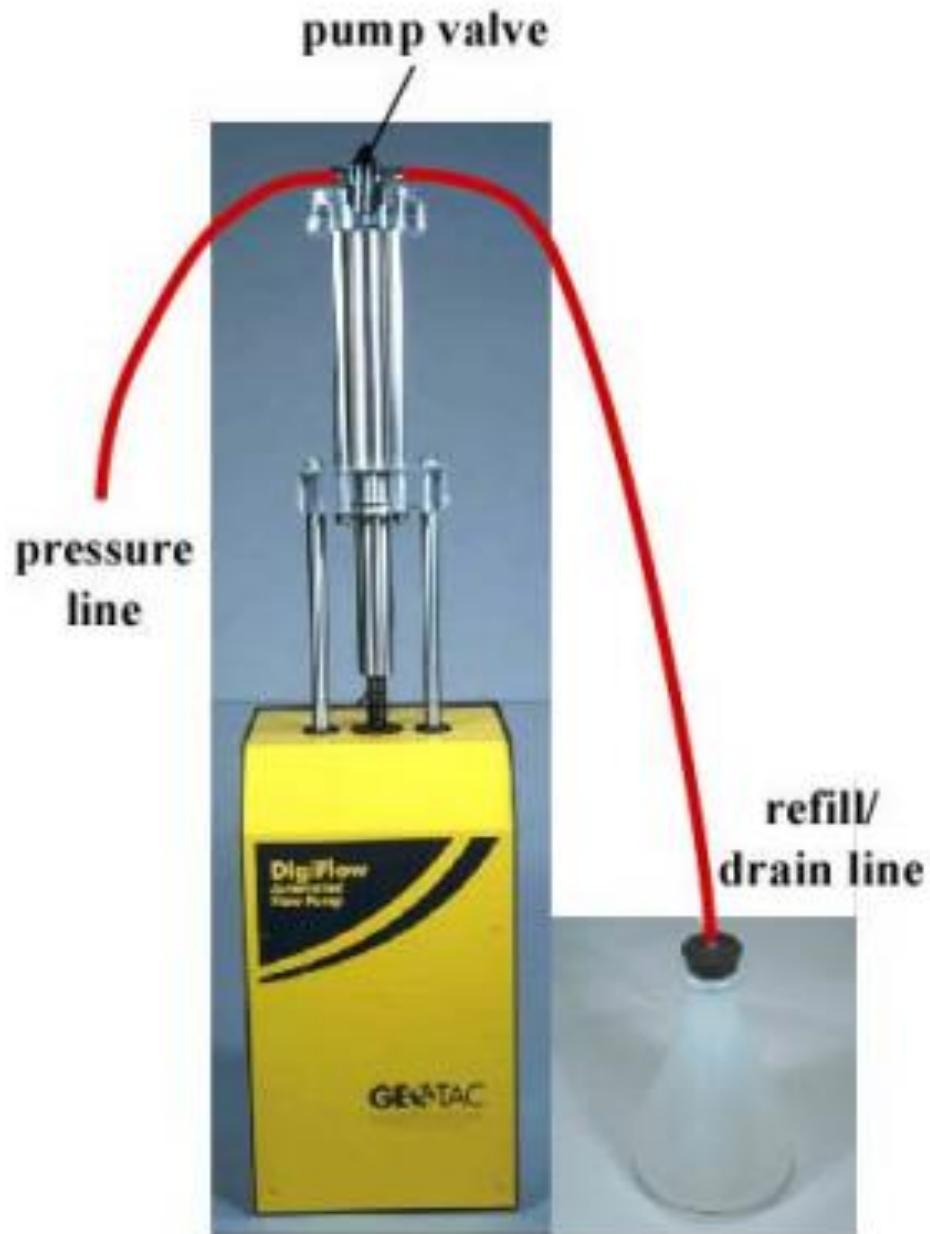


Figure 4.4 Pump lines used to fill the pump (refill/drain line) and connect to the triaxial cell (pressure line) (Trautwein Soil Testing Equipment Company, 2000).

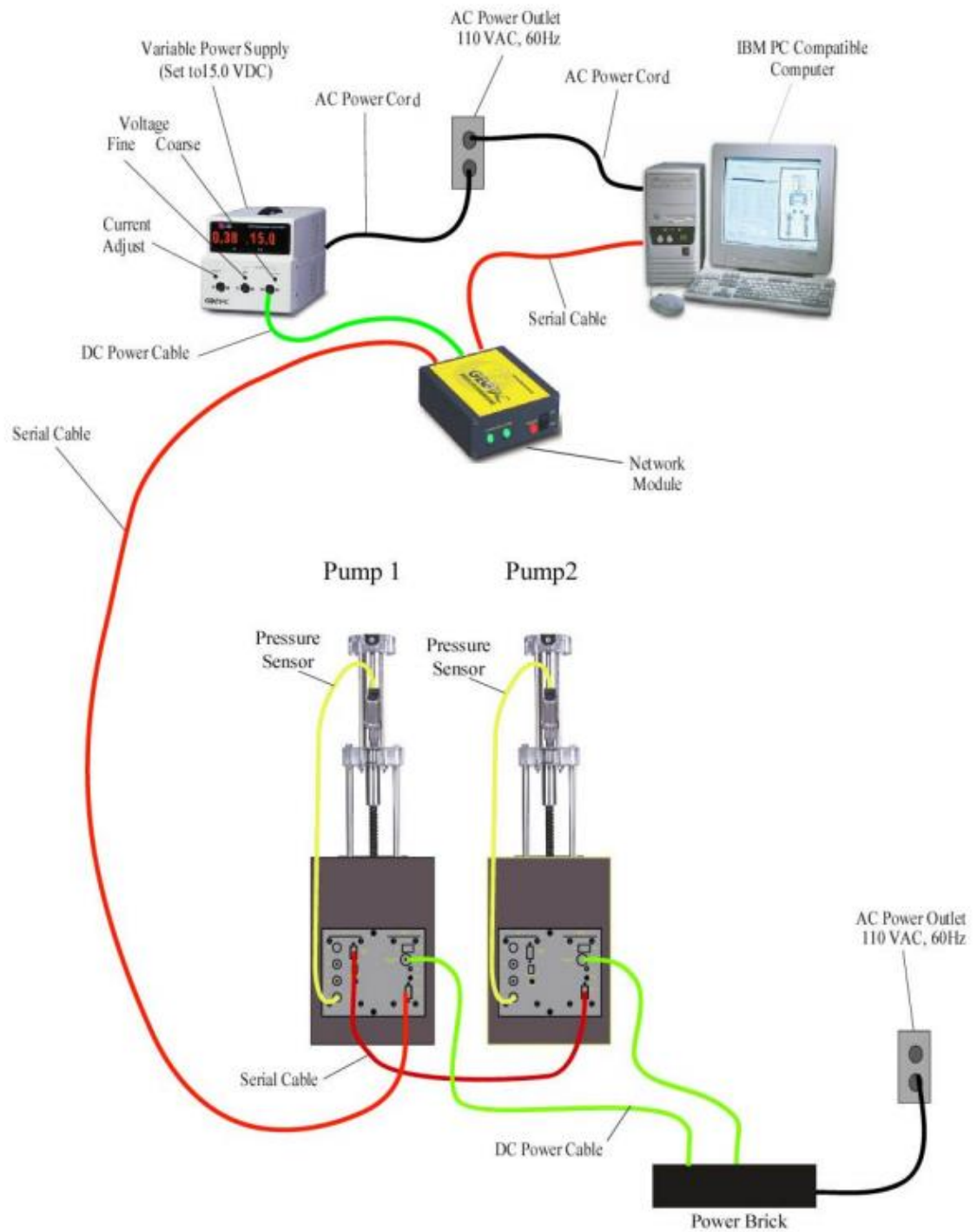


Figure 4.5 Schematic view of the DigiFlow system setup (Trautwein Soil Testing Equipment Company, 2000).

The DigiFlow-GP software allows for easy data acquisition using a user-friendly graphical interface. The specimen's dimensions were entered prior to testing in the "test data" menu and the type of test (isotropic) was specified with the strain-rate, maximum strain, and reading schedule. Four major steps are used in conducting a triaxial test with the software namely seating, saturation, consolidation, and shearing. The seating step was not used in this research because the piston needed to be lifted after applying some confining pressure to remove the top rubber band and open the split mold. The pumps and load frame can be controlled manually using either volume or pressure change for the pumps. For this study, the cell pressure pump was set to 10 kPa for the small confining pressure to make the specimen self-supporting. Once the sensor read 10 kPa, the piston was manually raised by hand slowly enough that the cell pressure did not drop below 7-8 kPa.

After the mold was opened and the piston was brought into contact with the top cap, saturation was performed by increasing cell pressure and doing a manual B-value check by closing the back pressure valve and increasing the cell pressure and observing how the pore-pressure reading changes using Equation 1 below. The DigiFlow-GP software automatically checks the B-value every 15 seconds after a cell pressure increase is specified. After the B-value check is finished, the DigiFlow-GP automatically reduces the cell pressure to its initial value.

$$B = \frac{\Delta u}{\Delta \sigma_3} \dots \dots \dots (1)$$

where:

Δu = change in pore-water-pressure of specimen as a result of the change in cell pressure

$\Delta \sigma_3$ = change in cell pressure

The cell pressure change corresponded to 20% of the cell pressure at the time of the B-value check. Since the material was initially almost completely saturated, saturation took a very short amount of time, and a relatively small amount of cell pressure.

Consolidation was performed by using a 5 kPa/hour rate of increase in cell pressure. Consolidation was terminated when the specimen pore-water volume change vs. time plot began to flatten out indicating that the excess pore water had completely dissipated. The consolidation process took between 7 and 8 hours to finish.

Shearing was performed by closing the valve to the back pressure pump and shearing at a rate of 0.5% axial strain/hour. Each stage was performed while graphically analyzing the data in real-time using the DigiFlow-GP software. Shearing was terminated between 15% and 25% after it was observed on the stress-strain plot that the specimen had failed - the deviator stress stopped increasing for increasing strain.

CHAPTER 5. MATERIALS TESTED

The material used in this research was pulverized EPK Kaolin clay from Edgar Minerals™. The chemical analysis of the Kaolin clay is shown below in Table 5.1 and some physical and ceramic properties of the clay in Table 5.2. The Atterberg limits were determined using the procedure from ASTM D4318-17. The liquid limit was determined to be 62% based on the data below in Table 5.3 and plotted in the semi-logarithmic plot of water content vs. number of blows in Figure 5.1 below. The plastic limit was determined to be 41% based on the average of two plastic limit tests seen in Table 5.4.

Table 5.1 *Chemical analysis of the EPK Kaolin clay used in this research.*

Mineral Type	Percentage	Mineral Type	Percentage
SiO ₂	45.73%	CaO	0.18
Al ₂ O ₃	37.36	Mgo	0.098
Fe ₂ O ₃	0.79	Na ₂ O	0.059
TiO ₂	0.37	K ₂ O	0.33
P ₂ O ₅	0.236	LOI	13.91

Table 5.2 *Physical and ceramic properties of the EPK Kaolin clay used in this research.*

Median Particle Size (Microns)	1.36
Specific Surface Area (m ² /g)	28.52
Mineral Content (X-Ray Diffraction)	Kaolinite (Al ₂ O ₃ , 2SiO ₂ , 2H ₂ O) - 97%
pH(10% Solids - Wt.)	5.8
Specific Gravity	2.65

Table 5.3 *Liquid limit raw test data of the pulverized Kaolinite clay.*

Sample No.	Number of Blows	Weight of Water (g)	Weight of Solids (g)	Water Content
1	18	5.00	7.73	65%
2	20	4.40	6.9	64%
3	26	5.57	9.21	61%
4	34	5.12	8.64	59%

Table 5.4 Plastic limit determination of the pulverized Kaolinite clay.

Weight of Water (g)	Weight of Solids (g)	Water Content
0.72	1.79	39%
1.91	4.48	43%

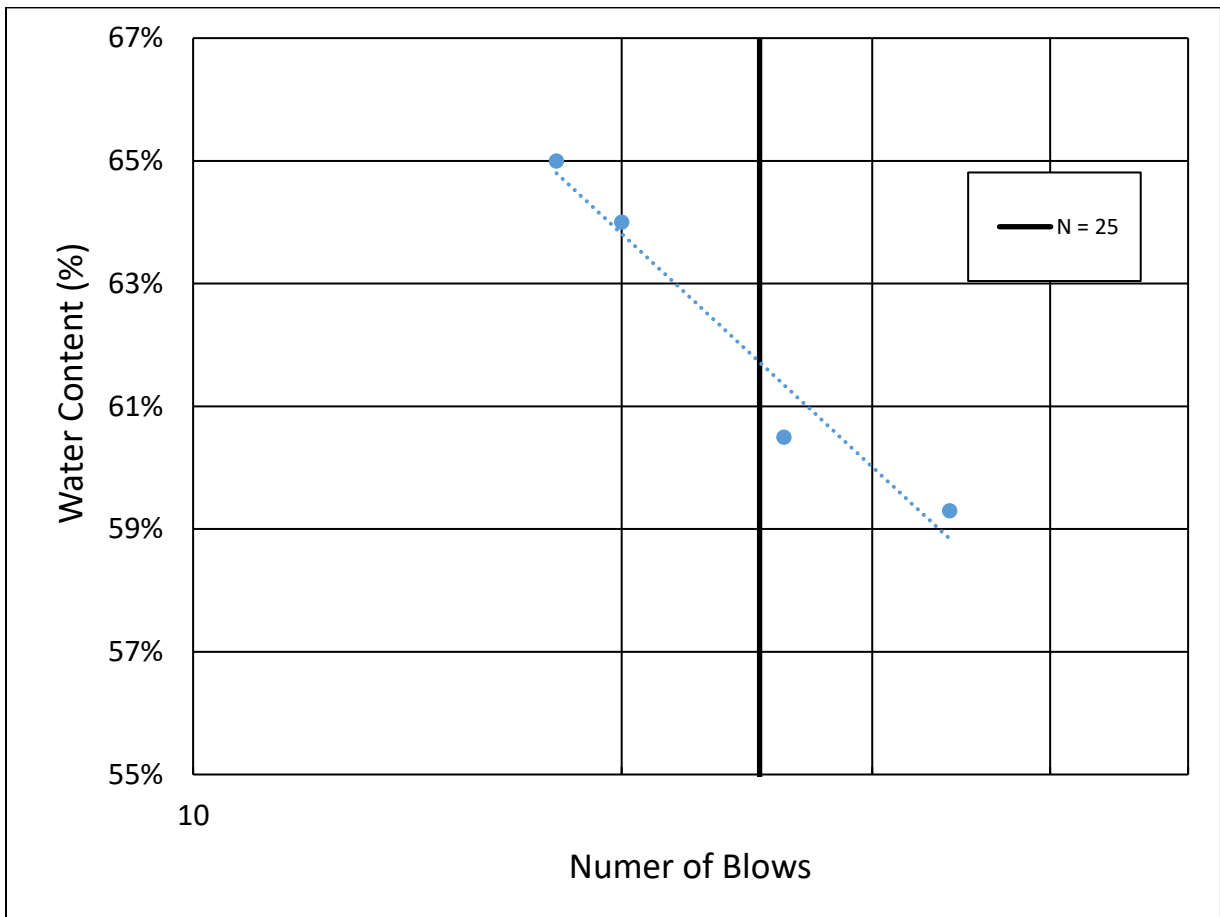


Figure 5.10 *Semi-logarithmic plot of water content vs. number of blows with N=25 indicated.*

CHAPTER 6. RESULTS

Three CUIC triaxial tests were carried out on the Kaolinite clay at a consolidation pressure of 30 kPa. The tests were carried out in three parts: saturation, consolidation, and shearing. A B-value of 0.98 corresponding to 98% saturation was easily achieved at or below a cell pressure of 100 kPa due to the slurry already having a high saturation. A constant effective stress of 5 kPa was held during saturation to avoid any unwanted pressure differentials. Consolidation was then performed by increasing the cell pressure at a rate of 5 kPa/hour. Full consolidation was achieved at approximately 500 minutes (8 hours 20 minutes). The volume change during consolidation was significant with 15 mL – 20 mL of water dissipating from the sample (Figure 6.1) corresponding to a volumetric strain of about 6.6% (Figure 6.2). This resulted in a water content of the clay tested during shearing equal to between 60% and 70% which is near or above its liquid limit.

The stress-strain curves from the three tests and the pore-water-pressure generation curves are shown in Figure 6.3 below. Table 6.1 summarizes the shear strength and pore-water-pressure at failure obtained from each test. The pore-water-pressure at failure show a significantly higher value than the deviator stress at failure resulting in an A_f pore-pressure parameter of approximately four.

The stress-strain curves show consistent failure values around 5.5 kPa and pore-water pressures at failure of about 23 kPa. In samples 1 and 3, an anomaly in the stress-strain response was found between 0.5% - 2% strain in which strain increased at a much smaller rate of pressure. This response could be due to a small pocket of air leaving the system, or a seating issue with the piston on the top cap.

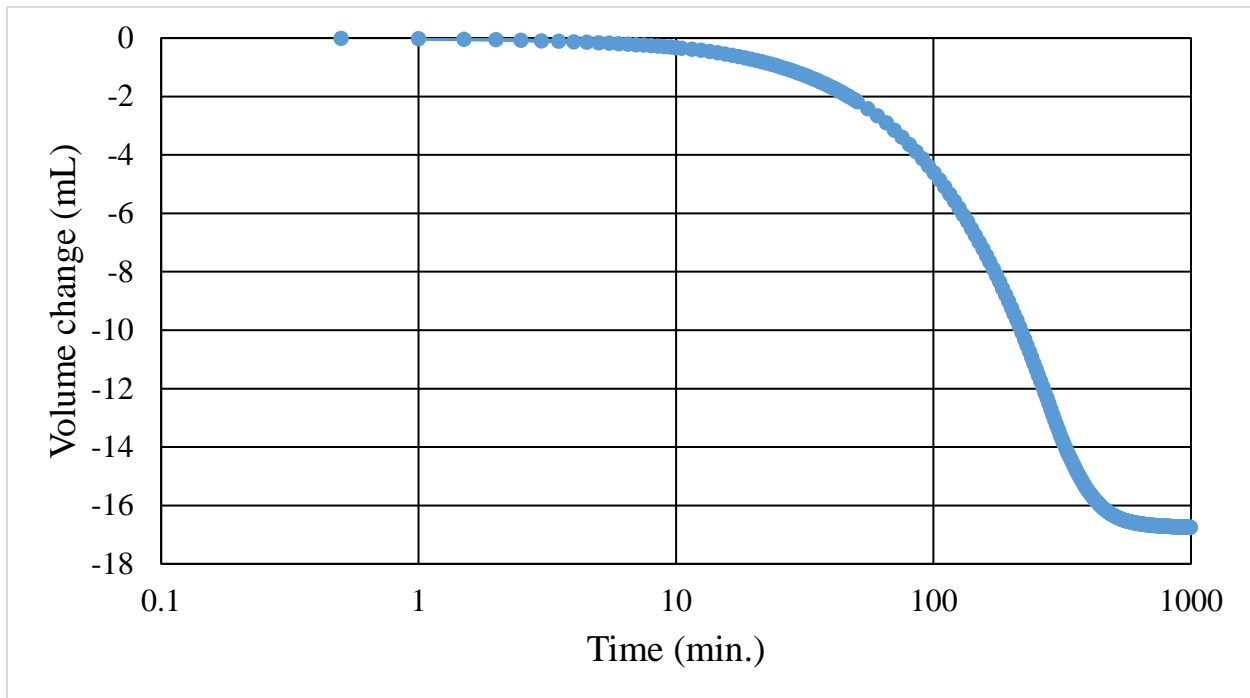


Figure 6.1 Consolidation curve for sample 1.

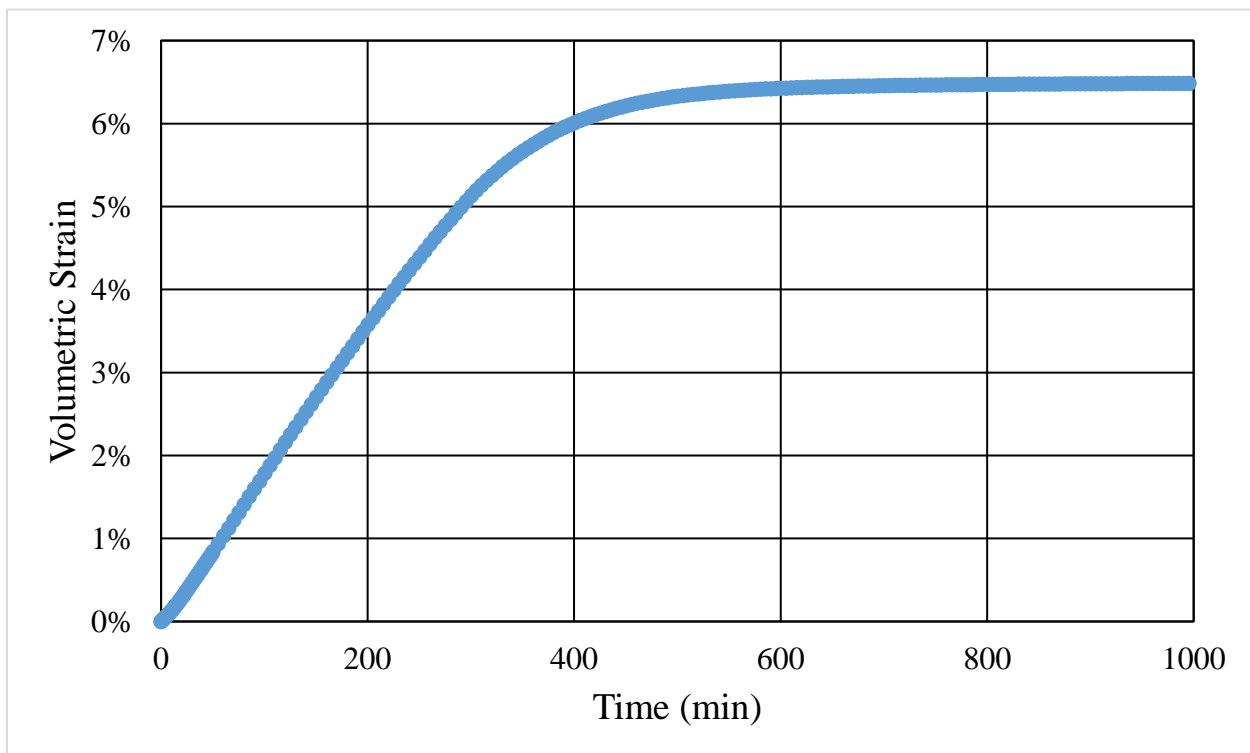


Figure 6.2 Volumetric strain vs. time of sample 1 during consolidation.

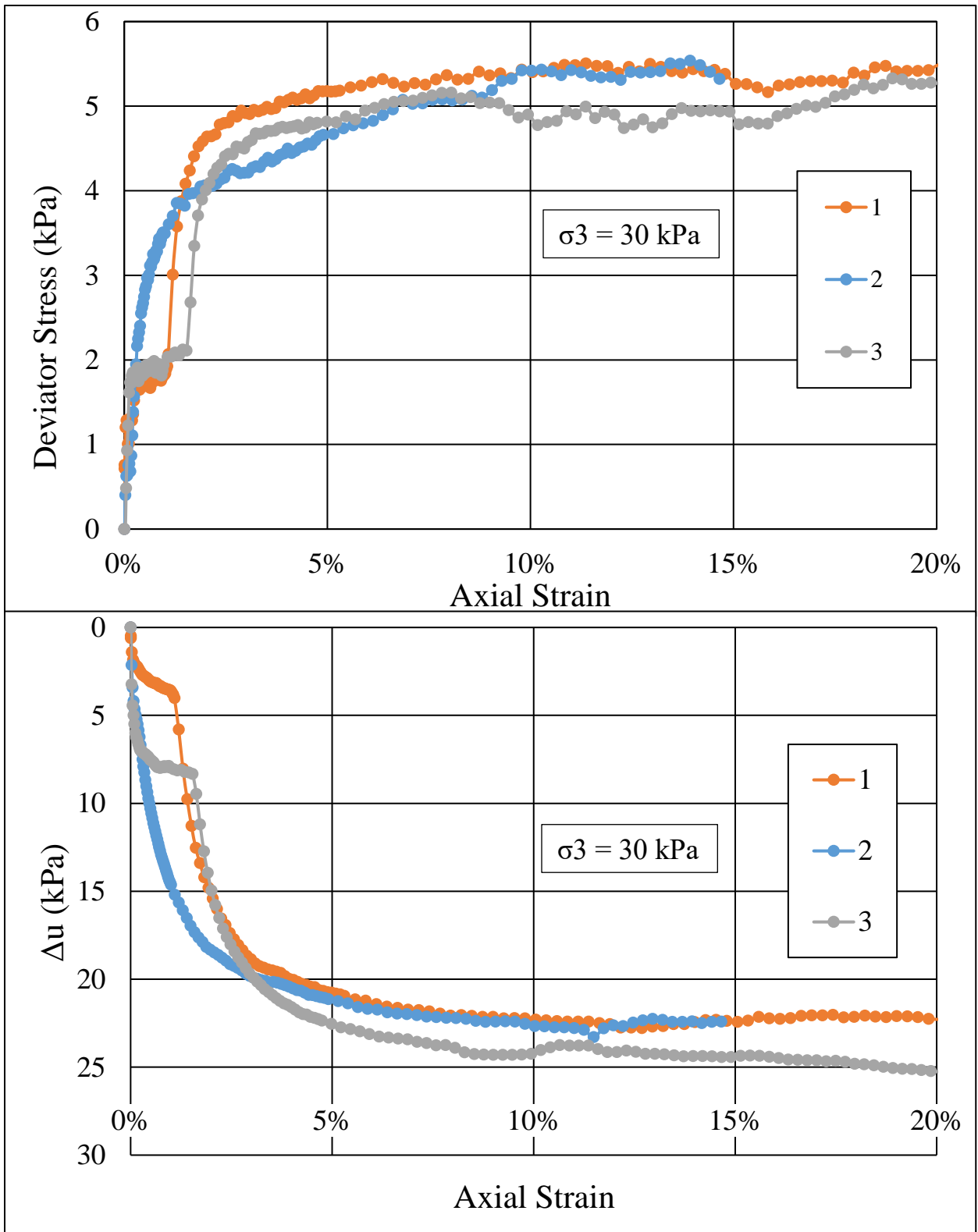


Figure 6.3 Deviator stress vs. strain (top) and change in pore-water-pressures (bottom) during the CUIC tests on Kaolinite clay.

Table 6.1 *Kaolinite shear strength values from the CUIC triaxial tests*

Sample No.	Undrained Shear Strength (kPa)	Δ PWP at Failure (kPa)	Af PWP parameter	S_u/σ'_v
1	5.5	22.7	4.13	0.18
2	5.5	22.4	4.06	0.18
3	5.3	24.8	4.68	0.18

Undrained shear strength divided by the effective consolidation pressure S_u/σ'_v is a parameter known as the undrained strength ratio used to normalize undrained shear strength to depth. The ratio can be used from data in the literature to compare to the values obtained in this research. Values of the undrained strength ratio for soft clays are known to be between 0.08 and 0.35 (Karlsrud and Hernandez-Martinez, 2013). The reconsolidation tank and T-Bar penetration tests from (Tufebkjian and Thompson, 2010) were discussed earlier as a method for testing soft soils in the laboratory at a consolidation pressure of 48 kPa. The undrained shear strength profile of the Kaolinite obtained from their data is shown below in Figure 6.4. The profile results in a S_u/σ'_v ratio of about 0.15 which is comparable to the 0.18 found in this research. Newson and Bransby (2004) analyzed the top few meters of a silty clay deposit in the Nile river delta using T-Bar and CPT data (Figure 6.5). They found a S_u/σ'_v ratio of 0.25 on average which is slightly higher but still comparable to what was found in this research. Table 6.2 summarizes the comparisons between S_u/σ'_v obtained in this research compared to the sources listed above.

Due to the inability to prepare a soft soil sample at low confining pressures for triaxial tests, there only exists S_u/σ'_v for pressures at minimum of between 150 kPa and 200 kPa.

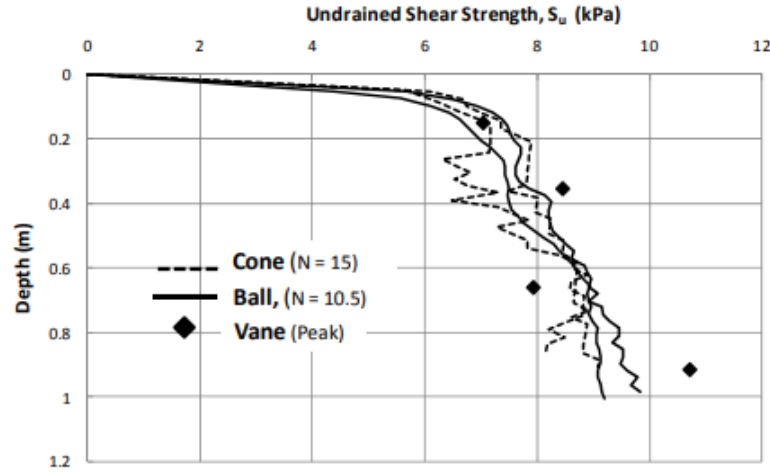


Fig. 8 Comparison of the undrained shear strength profiles for the cone, ball, and vane.

Figure 6.4 Undrained shear strength profiles from full flow penetrometers and vane shear in a reconsolidated Kaolin slurry tank consolidated at 48 kPa (Tufekjian and Thompson, 2010). Data corresponds to a S_u/σ'_v value of 0.15.

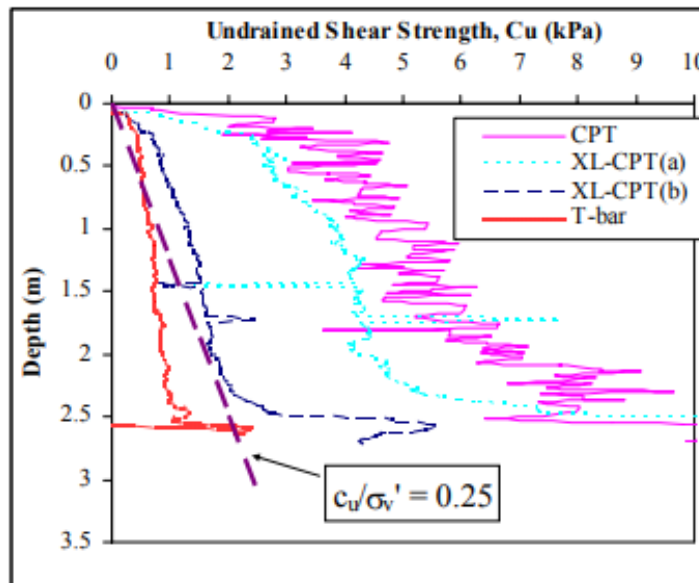


Figure 6.5 Undrained shear strength profile vs. depth for a silty clay from CPT and T-Bar data (Newson and Bransby, 2004).

Table 6.2 *Comparison of S_u/σ'_v to shallow in-situ methods used on Kaolin clays.*

S_u/σ'_v	Source	Method	Material Tested	Location/Sample Preparation	% Difference from present study
0.15	Tufebkjian and Thompson (2010)	T-Bar, VST	Kaolinite	Consolidation tank (top 2 meters)	-20%
0.17	Sahdi et al. (2015)	T-Bar	UWA Kaolin	Centrifuge (top 0.5 meters)	-6%
0.25	Newson and Bransby (2004)	CPT, T-Bar	Silty Clay	Nile River delta (top 3 meters)	28%

CHAPTER 7. CONCLUSIONS AND FUTURE WORK

Soft soils are difficult materials to prepare in an undisturbed manner that allows consolidation and shearing to be tested in one single process allowing for an accurate stress-strain response to be recorded. The split mold technique used to consolidate and shear soft clays from slurry that are non-self-supporting is a useful method for overcoming this dilemma. This method involves several steps that need to be taken with care to prevent disturbance to the soft, compressible soil sample. The results presented in this research show consistent stress-strain curves with reasonable values of undrained shear strength and undrained shear strength ratio as compared to field tests in similar soils at comparable depths.

The research presented in this thesis is a preliminary study to develop a split mold device like the one presented in Zhu et al. (2014) and successfully run CUIC tests on soft clays. Future work on this device would involve studying in more depth the behavior of the clay during the CUIC tests. These future studies should include testing the slurry at more consolidation pressures in order to obtain a Mohr-Coulomb cohesion and friction angle value, testing other types of clays or other soft, non-self-supporting materials in general, examining the clay fabric that is produced in the sample preparation methods, an improved design of the split mold that can be directly screwed into the base of the triaxial cell, and correcting for errors in the data acquisition process including using an internal load cell, and calculating a Young's modulus of the membrane. Several studies could be used to further this research and develop a more robust system for analyzing soil behavior.

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